ОЦЕНКА ВОЗМОЖНОСТИ ИСПОЛЬЗОВАНИЯ ЧЕРЕНКОВСКОГО ИЗЛУЧЕНИЯ ДЛЯ ОХЛАЖДЕНИЯ ПРОТОННОГО ПУЧКА ПО ЕГО ЭНЕРГЕТИЧЕСКИМ ПОТЕРЯМ

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THE ESTIMATION OF CHERENKOV RADIATION APPLICATION FOR PROTON BEAM COOLING ACCORDING TO ITS ENERGY LOSSES

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Аннотация. *Одной из основных задач современной физики ускорителей является увеличение энергии ускоренных заряженных частиц, изучение столкновения которых позволит ученым выйти за пределы Стандартной модели. Однако, с повышением энергии столкновения пучков, возрастают требования как к оборудованию, так и к характеристикам самого пучка. Одной из проблем при работе с протонными пучками является увеличение фазового объема пучка, так называемое «нагревание» протонов вследствие большого разброса кинетической энергии пучка. В данной статье рассматривается возможность использования излучения Вавилова-Черенкова для охлаждения высокоэнергетичных протонных пучков.*

Introduction. The Large Hadron Collider (LHC) is a two-ring-superconducting-hadron accelerator and collider built with the aim to reveal the physics beyond the Standard Model with center of mass collision energies of up to 14 TeV [1]. As much as proton colliders, LHC has the problem related to proton beams “heating”. In other words, the beam has the wide energy spread due to its transverse motion. To meet this challenge, the method of electron cooling was developed by G.I. Budker [2]. Nowadays, as the problem of “hot protons” arises with the beam energy growth; to satisfy such conditions new methods of protons cooling are investigated.

In the article the possibility of the use of dielectric targets, installed in the acceleration gap, for proton cooling is considered. The idea is based on the concept of polarization radiation arising as a result of dynamic polarization of media atomic shell by relativistic charged particle moving uniformly. There are different types of polarization radiation that differ by the character of optical inhomogeneities and the media where charged particle moves. When the charge moves with constant speed in media (or vacuum) along the boundary of dielectric target, the charge can lose its energy for Cherenkov radiation.

Approach. Let us consider the problem of radiation arising when a proton moves rectilinearly and uniformly in vacuum at the distance d from the dielectric target with permittivity $\varepsilon(\lambda)$ (Fig.1). According to the conditions of the LHC experiment, diamond is chosen as a target material.

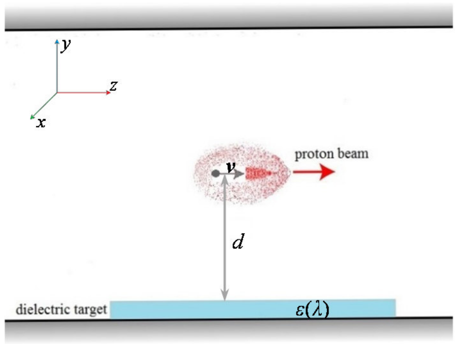

Fig. 1. Accelerated proton beam moving near the dielectric target with permittivity ε(λ)

There are several approaches for theoretical calculation of Cherenkov radiation characteristics. The one of them is the so-called method of images [3]. The method is based on the possibility to represent the field of charged particle as the ensemble of dipoles fields, arranged along the trajectory, and their imagines. Thus, by the Reciprocity theorem we can obtain the field of arbitrarily moving charged particle.

Assume that the target has infinite geometry along x and z axes as well as in negative direction along y-axis. When Cherenkov condition is satisfied only in the media of the target ($\varepsilon\beta^2>1$), all energy is radiated into the target. Intensity distribution along the generating lines of the Cherenkov cone is given by following equation [3]:

$$\frac{dW}{dz}=\frac{8\pi\alpha\hbar c}{\beta^2}\int\limits_{\lambda_{min}}^{\lambda_{max}}\frac{d\lambda}{\lambda^3}\int\limits_0^{\pi}d\varphi\frac{[(\varepsilon\beta^2-1)(\varepsilon_0+\varepsilon)\cos^2\varphi+\varepsilon(1-\varepsilon_0\beta^2)](\varepsilon\beta^2-1)\sin^2\varphi}{(\varepsilon-\varepsilon_0)[(\varepsilon_0+\varepsilon)\sin^2\varphi+\varepsilon\beta^2(\varepsilon\cos^2\varphi-\varepsilon_0\sin^2\varphi)]}\times$$

$$\times\, exp\left\{-d\frac{4\pi}{\beta\lambda}[(\varepsilon-\varepsilon_0)\beta^2-(\varepsilon\beta^2-1)\sin^2\varphi]^{1/2}\right\}, \quad (1)$$

where φ is the azimuth angle, β is the particle velocity at the speed of light units, $\varepsilon_0=1$ is the permittivity of vacuum, ε is the permittivity of the target as a function of wavelength λ, α = 1/137 is the fine structure constant, □c = 0.2 (eV/μm) is the conversion constant.

Results and Discussions. The dependence of permittivity on the wavelength for diamond, obtained from Sellmeier's equation [4], is presented in Figure 2.

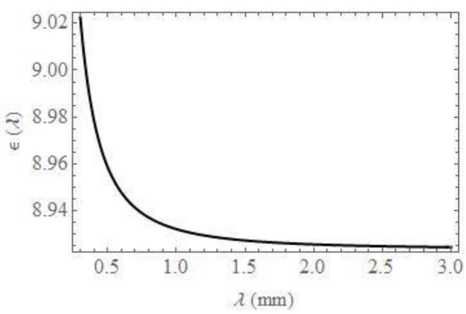

Fig. 2. The dependence of permittivity on the wavelength

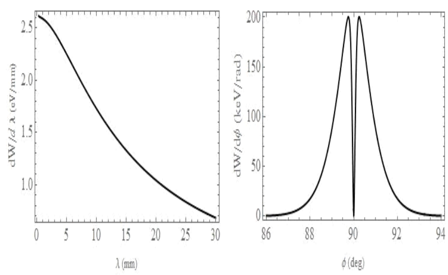

Fig. 3. The spectra and angular distribution of Cherenkov radiation

The calculations are made for the wavelength region within 0,3…3 mm (submillimeter waves). Such range is chosen because of the absorption properties of the target material are negligible in the concerned region. In this connection, the thermal degradation of the target will be decreased. As can be seen from Figure 2, the frequency dispersion (wavelength variation of the refractive index) is quite small (about 1%) and it decreases with the wavelength growth. The spectra and angular distribution of Cherenkov radiation are presented in Figure 3. Note that the results are obtained from the equation (1) after integrating over the azimuth angle for the beam with the concentration of 10^{11} and $d = 1$ cm upon condition that the beam covers the distance of 10 cm over the target. From the spectra we see that the proton beam will lose its energy for Cherenkov radiation more effectively in the submillimeter wavelength region.

The dependence of energy losses on the impact parameter d that obtained from the equation (1) after full integration is shown in Figure 3. From the obtained dependence we can conclude that the efficiency of the proton beam cooling has exponential dependence on impact parameter. The impact parameter will be defined according to the conditions of nonintersection with the target surface as well as effective damping radius of the particle Coulomb field, i.e. $d \leq \gamma\beta\lambda/(4\pi)$ (where $\gamma = \sqrt{1-\beta^2}$ is the particle's Lorenz-factor).

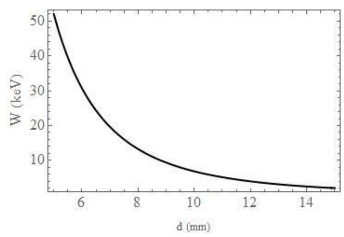

Fig. 4. The dependence of energy losses on the impact parameter d

Conclusion. According to the calculation, energy losses of the proton beam are 6,9 keV for required impact parameter value of 1 cm and the target length of 10 cm. As proton beam will moves within 26,7 km accelerated ring with the energy of 12 TeV, it will pass over the target $6{,}5\cdot 10^6$ times. It gives us 44,85 GeV of energy losses for the ring per second. The CERN requirement is 273 MeV energy losses per second. According this estimation, our method complies with the requirement and it can be applied for CERN experiments in proton beam cooling. Therefore, the relevance of further development of the theoretical method for the energy losses estimation has been shown. The aim of our future work is to develop the theoretical model for energy losses estimation allowing for finite size of the target, using the method of polarization currents [5].

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